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(6) AN EXAMINATION OF STATISTICAL IMPACT ACCELERATION INJURY PREDICTION MODELS BASED ON $-G_x$ ACCELERATOR DATA FROM SUBHUMAN PRIMATES.

by

(10) Dennis E. Smith

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TABLE OF CONTENTS

ACCESSION for
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JUSTIFICATION
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DISTRIBUTION/AVAILABILITY CODES
SPECIAL
A

I. INTRODUCTION

A previous technical report [1] discussed the use of a logistic function in development of an impact acceleration injury prediction model based on empirical data. Another report [2] described a Monte Carlo study conducted to assess the accuracy with which model parameters and injury probabilities could be estimated.

The model under consideration is based on the assumption of an underlying functional relationship of the form

$$P(\underline{x}) = \{1 + \exp[-(\beta_0 + \sum_{1}^{k}\beta_i x_i)]\}^{-1} \quad (1)$$

where:

$\underline{x} = (x_1,\ldots,x_k)$ denotes the set of independent variables considered,

$(\beta_0,\beta_1,\ldots,\beta_k)$ denotes a set of parameter values,

and $P(\underline{x})$ denotes the true probability of injury corresponding to $\underline{x}$.

This report considers the application of such a model to observed data from a set of twenty-eight $-G_x$ accelerator runs involving subhuman primates (Rhesus monkeys) with securely restrained torso and unrestrained head. The data was collected by the Naval Aerospace Medical Research Laboratory (NAMRL) Detachment as part of its research effort on acceleration impact injury prevention.

Two prediction models were constructed from this data, one based on head dynamic response only and the other based on sled acceleration profile only. The first model was derived from three variables distilled from head dynamic response time trace data. These three variables were:

(1) peak head angular acceleration (resultant) measured in radians/ sec^2,

(2) peak head linear acceleration (resultant) measured in meters/ sec^2,

and (3) peak head angular velocity (resultant) measured in radians/sec .

The second model was based on two variables describing sled acceleration:

(1) peak sled acceleration measured in G's

and (2) rate of sled acceleration onset measured in G/sec.

Surprisingly, the model based on sled profile variables provided better predictions than the model based on head dynamic response variables. Because of this, both sets of variables were combined into one overall five-variable set, which was then used in development of a prediction model. It was found that, for the relatively small amount of data available, inclusion of peak sled acceleration and any one of the other variables resulted in a model which yielded predictions in almost perfect agreement with the observations.

II. MODEL CONSTRUCTION

The data base used in model construction consisted of 28 observations from $-G_x$ accelerator runs on Rhesus monkeys. Because some of the monkeys were run more than once, dependence exists in the data. However, the assumption will be made that the effects of dependence are minor. If they do in fact exist, they should be reflected in a conservative model. (That is, because of the cumulative running, the model would predict probabilities that are too high.)

Because of the difficulty in defining injury, fatality was the criterion used in development of the models discussed in this report. Thus, the models are fatality prediction models, rather than injury prediction models. The complete data set is given in Figure 1. In this figure the observed probability of fatality for a given accelerator run is denoted by 1 for a fatal run and 0 for a nonfatal run.

Although the information is not necessary for model development, it should be noted that most fatalities involved a transection in the region between the lower medulla and upper cervical spinal cord. (See [3] for a further discussion of the neuropathological findings.)

A. ESTIMATION OF MODEL PARAMETERS

A computer program for maximum likelihood estimation was used to calculate $\hat{\beta}_0, \hat{\beta}_1, \ldots, \hat{\beta}_k$, i.e., the estimates of the parameters $\beta_0, \beta_1, \ldots, \beta_k$. It is possible, of course, that some or all of the candidate variables

Run Number	Subject Number	Observed Probability	Peak Sled Acceleration (z_1)	Rate of Sled Acceleration Onset (z_2)	Peak Head Angular Acceleration (x_1)	Peak Head Linear Acceleration (x_2)	Peak Head Angular Velocity (x_3)
LX1081	A03921	0	10.3	1531.5	1190.0	146.0	15.4
LX1082	A03921	0	39.8	871.9	4260.0	661.0	28.6
LX1083	A03921	0	38.3	3507.2	2005.0	645.0	12.8
LX1084	A03921	0	38.5	3827.7	6800.0	630.0	53.8
LX1085	A03921	0	38.2	3473.9	3110.0	635.0	25.6
LX1086	A03921	0	39.4	3823.9	3460.0	638.0	28.6
LX1087	A03921	0	39.5	3770.0	5635.0	728.0	44.2
LX1364	A03921	0	36.9	1612.4	5620.0	680.0	55.5
LX1365	A03921	1	108.7	13398.2	58100.0	9250.0	350.0
LX1359	A04099	0	106.9	16585.6	27200.0	2780.0	90.0
LX1360	A04099	1	128.2	21421.4	56400.0	5210.0	248.0
LX1362	A03935	0	105.5	17949.4	48800.0	4100.0	128.0
LX1363	A03935	1	123.0	20761.9	22800.0	1945.0	106.0
LX1891	A03943	0	83.7	6325.8	29800.0	1955.0	150.0
LX1892	A03948	0	83.5	7333.1	22000.0	1640.0	137.0
LX1893	A03924	0	110.3	9292.4	31000.0	2400.0	142.0
LX1894	A03933	0	108.4	9291.1	31700.0	2540.0	138.0
LX1895	A03951	1	130.5	12682.0	49200.0	2850.0	220.0
LX1896	A03946	1	131.3	14961.5	26500.0	2485.0	105.0
LX1889	A04101	0	34.8	1611.7	9650.0	1460.0	134.0
LX1890	A04101	0	33.2	1559.1	5695.0	618.0	48.0
LX1898	A04101	0	32.5	1582.8	4010.0	664.0	43.0
LX1899	A04101	0	32.4	1411.0	3450.0	580.0	40.0
LX1900	A04101	0	74.7	5683.2	14500.0	1540.0	90.0
LX1901	A04101	0	74.6	5411.0	11600.0	1685.0	75.5
LX1902	A04101	0	75.5	6224.5	7990.0	1775.0	31.2
LX1903	A04101	0	75.2	6299.7	10800.0	1795.0	39.3
LX1905	A04101	1	126.2	13796.9	16700.0	2820.0	52.8

Figure 1: The Data Set

may prove unimportant and should therefore not be included in a final model. To judge the contribution of variables, likelihood-ratio tests may be conducted. This procedure may be used in conjunction with "nested" models.

In the present context, one model will be said to be nested within another if the second model contains all variables of the first model plus one or more additional variables. Thus, a model which contained variables x_1, x_2 and x_3 would be nested within a model which contained only x_1 and x_2.

To test a hypothesis that a model containing variables $(x_1,\ldots,x_{k+m})$ is a significant improvement over a model containing variables $(x_1,\ldots,x_k)$, a Chi-square statistic may be used. The procedure is to calculate:

L_1 = -2 log likelihood for model containing $(x_1,\ldots,x_k)$

and L_2 = -2 log likelihood for model containing $(x_1,\ldots,x_{k+m})$.

Under the null hypothesis that the m additional variables $(x_{k+1},\ldots,x_{k+m})$ do not result in an improved model, the statistic $L_1 - L_2$ has an approximate Chi-square distribution with m degrees of freedom. Thus, the hypothesis may be tested by comparing the value of $L_1 - L_2$ with the upper percentage points of the appropriate Chi-square distribution.

B. HEAD DYNAMIC RESPONSE VARIABLES

As previously mentioned, three head dynamic response variables were considered in model development. In the following discussion these variables will be denoted by x_1, x_2, and x_3, where:

x_1 is peak head angular acceleration (resultant) measured in radians/ sec^2,

x_2 is peak head linear acceleration (resultant) measured in meters/ sec^2 ,

and x_3 is peak head angular velocity (resultant) measured in radians/sec . The first stage in model construction based on variables x_1, x_2 and x_3 involved examination of all possible models including these variables or any subset.

For a given number of variables, that model which yielded the smallest -2 log likelihood value was selected as the "best". As can be seen from Figure 2, the best one-variable, two-variable, and three-variable models are those based on, respectively,

(1) x_2

(2) x_2, x_3

(3) x_1, x_2, x_3 .

Because of the nesting in these models, the relative contribution of variables x_2, x_3, and x_1 may be tested in that order.

Figure 3 presents a summary of the relevant test procedure. In the first stage, x_2 was tested to determine whether it significantly improved a model which assumed constant probability over all values of the three head dynamic response variables. The observed Chi-square value of 11.26, which is statistically significant at the .0008 level, indicated that this variable did result in an improved model.

The second stage of testing involved consideration of the addition of another variable to the model which included only variable x_2 . Because the best two-variable model was based on x_2 and x_3, the effect

Variable Set	-2 Log Likelihood
Constant Only	29.10
x_1	19.30
x_2	17.84
x_3	19.89
x_1, x_2	17.82
x_1, x_3	19.07
x_2, x_3	17.47
x_1, x_2, x_3	16.91

x_1 denotes peak head angular acceleration

x_2 denotes peak head linear acceleration

x_3 denotes peak head angular velocity

Figure 2: Head Dynamic Response Variable Sets and Associated -2 Log Likelihood Values

Test 1: x_2 against Constant Only

$$L_1 - L_2 = 29.10 - 17.84 = 11.26 \text{ (1 d.f., } p = .0008)$$
Significant

Test 2: (x_2, x_3) against x_2

$$L_1 - L_2 = 17.84 - 17.47 = 0.37 \text{ (1 d.f., } p > .50)$$
Nonsignificant

Test 3: (x_1, x_2, x_3) against x_2

$$L_1 - L_2 = 17.84 - 16.91 = 0.93 \text{ (2 d.f., } p > .50)$$
Nonsignificant

x_1 denotes peak head angular acceleration

x_2 denotes peak head linear acceleration

x_3 denotes peak head angular velocity

Figure 3: Testing the Significance of the Head Dynamic Response Variables

of including the latter variable was examined. The addition of x_3 to the model resulted in an observed Chi-square value of 0.37, which is not statistically significant. Likewise, a model based on all three variables (x_1, x_2, x_3), when tested against the model based on x_2 only, resulted in a statistically nonsignificant Chi-square value of 0.93.

Thus, based on the set of data under consideration, a predictive model which includes only variable x_2 appears to provide the best results. It is interesting to note that x_2 is a linear component, while both x_1 and x_3 are angular components. This provides some tentative empirical evidence that, for $-G_x$ acceleration, the primary component correlating with impact acceleration injury (more correctly, fatality) may be linear rather than angular. However, this evidence is far from conclusive because of the small data base and the high degree of intercorrelations between the observed values of the variables.

The resulting model is given by:

$$\hat{P}(x_2) = \{1 + \exp[-(-4.344 + 0.001369\ x_2)]\}^{-1} \qquad (2)$$

where, of course, $\hat{P}(x_2)$ denotes the fitted model. Figure 4 presents, for this model, a comparison of observed probability (i.e., 0 or 1) and predicted probability, where the observations are arranged in order of increasing predicted probability. As can be seen from this figure, there is reasonable agreement between predictions and observations.

C. SLED PROFILE VARIABLES

A procedure similar to that described in the previous section was

Run Number	Subject Number	Observed Probability	Predicted Probability	Peak Head Linear Acceleration (x_2)
LX1081	A03921	0	0.0156	146.0
LX1899	A04101	0	0.0279	580.0
LX1890	A04101	0	0.0294	618.0
LX1084	A03921	0	0.0298	630.0
LX1085	A03921	0	0.0300	635.0
LX1086	A03921	0	0.0302	638.0
LX1083	A03921	0	0.0304	645.0
LX1082	A03921	0	0.0311	661.0
LX1898	A04101	0	0.0312	664.0
LX1364	A03921	0	0.0319	680.0
LX1087	A03921	0	0.0340	728.0
LX1889	A04101	0	0.0874	1460.0
LX1900	A04101	0	0.0966	1540.0
LX1892	A03948	0	0.1092	1640.0
LX1901	A04101	0	0.1153	1685.0
LX1902	A04101	0	0.1285	1775.0
LX1903	A04101	0	0.1316	1795.0
LX1363	A03935	1	0.1569	1945.0
LX1891	A03943	0	0.1587	1955.0
LX1893	A03924	0	0.2576	2400.0
LX1896	A03946	1	0.2805	2485.0
LX1894	A03933	0	0.2959	2540.0
LX1359	A04099	0	0.3686	2780.0
LX1905	A04101	1	0.3814	2820.0
LX1895	A03951	1	0.3912	2850.0
LX1362	A03935	0	0.7806	4100.0
LX1360	A04099	1	0.9421	5210.0
LX1365	A03921	1	0.9998	9250.0

Figure 4: A Comparison of Observed and Predicted Probability for Model Based on Peak Head Linear Acceleration

applied to two sled profile variables which in the following discussion are denoted by z_1 and z_2, where

z_1 is peak sled acceleration measured in G's

and z_2 is rate of sled acceleration onset measured in G/sec .

As Figure 5 indicates, the "best" one-variable model is based on z_1 .

Figure 6 provides a comparison of predicted and observed probability for this model, which is given by

$$\hat{P}(z_1) = \{1 + \exp[-(-49.81 + 0.4472\ z_1)]\}^{-1} . \qquad (3)$$

As can be seen from this figure, the agreement between predictions and observations, although not perfect, is relatively good.

Figure 7 summarizes the testing of the model improvement resulting from the inclusion of variables z_1 and z_2 in that order. The results of the test in the first stage (observed Chi-square value of 24.34, statistically significant at the .0001 level) indicated that variable z_1 provided an improved model. Likewise, the second stage of testing showed that z_2 should be included in the model also, since the observed Chi-square value was 4.75, which is statistically significant at the .029 level.

The resulting fitted model based on both variables z_1 and z_2 is given by

$$\hat{P}(z_1,z_2) = \{1 + \exp[-(-4463.0 + 38.88\ z_1 + .01816\ z_2)]\}^{-1} \qquad (4)$$

A comparison of observed 0/1 probabilities with predicted probabilities is given in Figure 8. As indicated in this figure, the agreement between observed and predicted probability is almost perfect.

Variable Set	-2 Log Likelihood
Constant Only	29.10
z_1	4.76
z_2	13.92
z_1, z_2	0.01

z_1 denotes peak sled acceleration

z_2 denotes rate of sled acceleration onset

Figure 5: Sled Acceleration Profile Variable Sets and Associated -2 Log Likelihood Values

Run Number	Subject Number	Observed Probability	Predicted Probability	Peak Sled Acceleration (z_1)
LX1081	A03921	0	0.0000	10.3
LX1899	A04101	0	0.0000	32.4
LX1898	A04101	0	0.0000	32.5
LX1890	A04101	0	0.0000	33.2
LX1889	A04101	0	0.0000	34.8
LX1364	A03921	0	0.0000	36.9
LX1085	A03921	0	0.0000	38.2
LX1083	A03921	0	0.0000	38.3
LX1084	A03921	0	0.0000	38.5
LX1086	A03921	0	0.0000	39.4
LX1087	A03921	0	0.0000	39.5
LX1082	A03921	0	0.0000	39.8
LX1901	A04101	0	0.0000	74.6
LX1900	A04101	0	0.0000	74.7
LX1903	A04101	0	0.0000	75.2
LX1902	A04101	0	0.0000	75.5
LX1892	A03948	0	0.0000	83.5
LX1891	A03943	0	0.0000	83.7
LX1362	A03935	0	0.0672	105.5
LX1359	A04099	0	0.1187	106.9
LX1894	A03933	0	0.2086	108.4
LX1365	A03921	1	0.2316	108.7
LX1893	A03924	0	0.3813	110.3
LX1363	A03935	1	0.9945	123.0
LX1905	A04101	1	0.9987	126.2
LX1360	A04099	1	0.9995	128.2
LX1895	A03951	1	0.9998	130.5
LX1896	A03946	1	0.9999	131.3

Figure 6: A Comparison of Observed and Predicted Probability for Model Based on Peak Sled Acceleration

Test 1: z_1 against Constant Only

$$L_1 - L_2 = 29.10 - 4.76 = 24.34 \text{ (1 d.f., } p = .0001)$$

Significant

Test 2: (z_1, z_2) against z_1

$$L_1 - L_2 = 4.76 - 0.01 = 4.75 \text{ (1 d.f., } p = .0293)$$

Significant

z_1 denotes peak sled acceleration

z_2 denotes rate of sled acceleration onset

Figure 7: Testing the Significance of the Sled Acceleration Profile Variables

Run Number	Subject Number	Observed Probability	Predicted Probability	Peak Sled Acceleration (z_1)	Rate of Sled Acceleration Onset (z_2)
LX1081	A03921	0	0.0000	10.3	1531.5
LX1082	A03921	0	0.0000	39.8	871.9
LX1083	A03921	0	0.0000	38.3	3507.2
LX1084	A03921	0	0.0000	38.5	3827.7
LX1085	A03921	0	0.0000	38.2	3473.9
LX1086	A03921	0	0.0000	39.4	3823.9
LX1087	A03921	0	0.0000	39.5	3770.0
LX1364	A03921	0	0.0000	36.9	1612.4
LX1889	A04101	0	0.0000	34.8	1611.7
LX1892	A03948	0	0.0000	83.5	7333.1
LX1891	A03943	0	0.0000	83.7	6325.8
LX1903	A04101	0	0.0000	75.2	6299.7
LX1900	A04101	0	0.0000	74.7	5683.2
LX1898	A04101	0	0.0000	32.5	1582.8
LX1890	A04101	0	0.0000	33.2	1559.1
LX1901	A04101	0	0.0000	74.6	5411.0
LX1902	A04101	0	0.0000	75.5	6224.5
LX1899	A04101	0	0.0000	32.4	1411.0
LX1894	A03933	0	0.0000	108.4	9291.1
LX1362	A03935	0	0.0000	105.5	17949.4
LX1893	A03924	0	0.0031	110.3	9292.4
LX1359	A04099	0	0.0039	106.9	16585.6
LX1365	A03921	1	0.9986	108.7	13398.2
LX1363	A03935	1	1.0000	123.0	20761.9
LX1896	A03946	1	1.0000	131.3	14961.5
LX1895	A03951	1	1.0000	130.5	12682.0
LX1360	A04099	1	1.0000	128.2	21421.4
LX1905	A04101	1	1.0000	126.2	13796.9

Figure 8: A Comparison of Observed and Predicted Probability for Model Based on Peak Sled Acceleration and Rate of Sled Acceleration Onset

D. COMBINED HEAD AND SLED VARIABLES

In the two previous sections the three head dynamic response variables and the two sled profile variables were regarded as defining two separate, independent sets of variables. In this section, these five variables are considered as comprising one overall set from which prediction models are developed.

As Figure 9 indicates, z_1 (peak sled acceleration) provided the best-fitting one-variable model. From this figure it can also be seen that four models are, for all practical purposes, tied in the competition for the best two-variable model. These are the models based on (z_1, x_1), (z_1, x_2), (z_1, x_3), and (z_1, z_2).

In general, the testing procedure involves a test of z_1 against a constant probability model followed by a test of whether the addition of a second variable provides significant improvement. Because the -2 log likelihood values for the addition of any one of the four variables x_1, x_2, x_3, or z_2 to the model are essentially the same (0.00 or 0.01), the test results are equivalent to those illustrated for z_2 in Figure 7.

By examining Figure 8 and Figures 10 through 12, it can be seen that any of the four variable pairs result in a model which yields predictions in almost perfect agreement with the observed data. The model involving z_1 and z_2 is given by (4) in the previous section. The three remaining models are:

$$\hat{P}(z_1, x_1) = \{1 + \exp[-(-354.0 + 2.767z_1 + 0.00108x_1)]\}^{-1} \quad (5)$$

$$\hat{P}(z_1, x_2) = \{1 + \exp[-(-196.7 + 1.622z_1 + 0.00345x_2)]\}^{-1} \quad (6)$$

$$\hat{P}(z_1, x_3) = \{1 + \exp[-(-248.6 + 2.009z_1 + 0.11938x_3)]\}^{-1} \quad (7)$$

Variable Set	-2 Log Likelihood
Constant Only	29.10
x_1	19.30
x_2	17.84
x_3	19.89
z_1	4.76
z_2	13.92
x_1, x_2	17.82
x_1, x_3	19.07
x_1, z_1	0.00
x_1, z_2	13.46
x_2, x_3	17.47
x_2, z_1	0.00
x_2, z_2	12.77
x_3, z_1	0.00
x_3, z_2	11.74
z_1, z_2	0.01

x_1 denotes peak head angular acceleration
x_2 denotes peak head linear acceleration
x_3 denotes peak head angular velocity
z_1 denotes peak sled acceleration
z_2 denotes rate of sled acceleration onset

Figure 9: Head and Sled Acceleration Variable Sets and Associated -2 Log Likelihood Values

Run Number	Subject Number	Observed Probability	Predicted Probability	Peak Sled Acceleration (z_1)	Peak Head Angular Acceleration (x_1)
LX1081	A03921	0	0.0000	10.3	1190.0
LX1082	A03921	0	0.0000	39.8	4260.0
LX1083	A03921	0	0.0000	38.3	2005.0
LX1084	A03921	0	0.0000	38.5	6800.0
LX1085	A03921	0	0.0000	38.2	3110.0
LX1086	A03921	0	0.0000	39.4	3460.0
LX1087	A03921	0	0.0000	39.5	5635.0
LX1364	A03921	0	0.0000	36.9	5620.0
LX1889	A04101	0	0.0000	34.8	9650.0
LX1892	A03948	0	0.0000	83.5	22000.0
LX1891	A03943	0	0.0000	83.7	29800.0
LX1903	A04101	0	0.0000	75.2	10800.0
LX1900	A04101	0	0.0000	74.7	14500.0
LX1898	A04101	0	0.0000	32.5	4010.0
LX1890	A04101	0	0.0000	33.2	5695.0
LX1901	A04101	0	0.0000	74.6	11600.0
LX1902	A04101	0	0.0000	75.5	7990.0
LX1899	A04101	0	0.0000	32.4	3450.0
LX1359	A04099	0	0.0000	106.9	27200.0
LX1894	A03933	0	0.0000	108.4	31700.0
LX1893	A03924	0	0.0000	110.3	31000.0
LX1362	A03935	0	0.0001	105.5	48800.0
LX1365	A03921	1	0.9999	108.7	58100.0
LX1363	A03935	1	1.0000	123.0	22800.0
LX1905	A04101	1	1.0000	126.2	16700.0
LX1895	A03951	1	1.0000	130.5	49200.0
LX1360	A04099	1	1.0000	128.2	56400.0
LX1896	A03946	1	1.0000	131.3	26500.0

Figure 10: A Comparison of Observed and Predicted Probability for Model Based on Peak Sled Acceleration and Peak Head Angular Acceleration

Run Number	Subject Number	Observed Probability	Predicted Probability	Peak Sled Acceleration (z_1)	Peak Head Linear Acceleration (x_2)
LX1081	A03921	0	0.0000	10.3	146.0
LX1082	A03921	0	0.0000	39.8	661.0
LX1083	A03921	0	0.0000	38.3	645.0
LX1084	A03921	0	0.0000	38.5	630.0
LX1085	A03921	0	0.0000	38.2	635.0
LX1086	A03921	0	0.0000	39.4	638.0
LX1087	A03921	0	0.0000	39.5	728.0
LX1364	A03921	0	0.0000	36.9	680.0
LX1899	A04101	0	0.0000	32.4	580.0
LX1889	A04101	0	0.0000	34.8	1460.0
LX1898	A04101	0	0.0000	32.5	664.0
LX1890	A04101	0	0.0000	33.2	618.0
LX1900	A04101	0	0.0000	74.7	1540.0
LX1901	A04101	0	0.0000	74.6	1685.0
LX1903	A04101	0	0.0000	75.2	1795.0
LX1902	A04101	0	0.0000	75.5	1775.0
LX1892	A03948	0	0.0000	83.5	1640.0
LX1891	A03943	0	0.0000	83.7	1955.0
LX1359	A04099	0	0.0000	106.9	2780.0
LX1894	A03933	0	0.0000	108.4	2540.0
LX1362	A03935	0	0.0000	105.5	4100.0
LX1893	A03924	0	0.0001	110.3	2400.0
LX1363	A03935	1	0.9999	123.0	1945.0
LX1365	A03921	1	1.0000	108.7	9250.0
LX1896	A03946	1	1.0000	131.3	2485.0
LX1895	A03951	1	1.0000	130.5	2850.0
LX1360	A04099	1	1.0000	128.2	5210.0
LX1905	A04101	1	1.0000	126.2	2820.0

Figure 11: A Comparison of Observed and Predicted Probability of Model Based on Peak Sled Acceleration and Peak Head Linear Acceleration

Run Number	Subject Number	Observed Probability	Predicted Probability	Peak Sled Acceleration (z_1)	Peak Head Angular Velocity (x_3)
LX1081	A03921	0	0.0000	10.3	15.4
LX1082	A03921	0	0.0000	39.8	28.6
LX1083	A03921	0	0.0000	38.3	12.8
LX1084	A03921	0	0.0000	38.5	53.8
LX1085	A03921	0	0.0000	38.2	25.6
LX1086	A03921	0	0.0000	39.4	28.6
LX1087	A03921	0	0.0000	39.5	44.2
LX1364	A03921	0	0.0000	36.9	55.5
LX1889	A04101	0	0.0000	34.8	134.0
LX1903	A04101	0	0.0000	75.2	39.3
LX1900	A04101	0	0.0000	74.7	90.0
LX1898	A04101	0	0.0000	32.5	43.0
LX1890	A04101	0	0.0000	33.2	48.0
LX1901	A04101	0	0.0000	74.6	75.5
LX1902	A04101	0	0.0000	75.5	31.2
LX1899	A04101	0	0.0000	32.4	40.0
LX1892	A03948	0	0.0000	83.5	137.0
LX1891	A03943	0	0.0000	83.7	150.0
LX1359	A04099	0	0.0000	106.9	90.0
LX1362	A03935	0	0.0000	105.5	128.0
LX1894	A03933	0	0.0000	108.4	138.0
LX1893	A03924	0	0.0000	110.3	142.0
LX1363	A03935	1	1.0000	123.0	106.0
LX1905	A04101	1	1.0000	126.2	52.8
LX1365	A03921	1	1.0000	108.7	350.0
LX1896	A03946	1	1.0000	131.3	105.0
LX1895	A03951	1	1.0000	130.5	220.0
LX1360	A04099	1	1.0000	128.2	248.0

Figure 12: A Comparison of Observed and Predicted Probability of Model Based on Peak Sled Acceleration and Peak Head Angular Velocity

In summary, it may be stated that, based on the data set considered, peak sled acceleration is the single most useful variable in making accurate predictions. However, its effectiveness can be significantly improved by adding any one of the four other variables:

(a) z_2, rate of sled acceleration onset

(b) x_1, peak head angular acceleration

(c) x_2, peak head linear acceleration

(d) x_3, peak head angular velocity.

E. PREDICTION OF CRITICAL ENVELOPES

From a fitted model such as (2) through (7), a critical envelope can be predicted. This envelope defines those combinations of independent variables for which the predicted probability of injury (or fatality) is greater than some given amount. In the present situation, suppose it were desired to restrict the variable values to a region in which the probability of fatality were less than some small probability P_0 (such as .01 or .05). In other words, the predicted probability $\hat{P}(\underline{x})$ would be less than P_0 . From this it follows that:

$$\hat{P}(\underline{x}) \leq P_0$$

$$\{1 + \exp[-(\hat{\beta}_0 + \sum_1^k \hat{\beta}_i x_i)]\}^{-1} \leq P_0$$

$$\hat{\beta}_0 + \sum_1^k \hat{\beta}_i x_i \leq \ln[P_0/(1 - P_0)] \; .$$

From the fitted head dynamic response model given by (2), the critical envelope at $P_0 = .05$ is

$$-4.344 + .001369x_2 \leq -2.944$$

or equivalently,

$$x_2 \leq 1022.6 .$$

Thus, the probability of fatality is predicted to be less than 5% if peak head linear acceleration is less than 1022.6 radians/sec^2 . This is shown graphically in Figure 13.

Similarly, the critical envelope at P_0 = .05 based on sled profile variables incorporated into fitted model (4) is

$$-4463.0 + 38.80z_1 + .01816z_2 \leq -2.944$$

or equivalently,

$$2136.56z_1 + z_2 \leq 245{,}598.01 .$$

This is shown graphically in Figure 14. The 5% critical envelopes for the other three variable pairs are illustrated in Figures 15 through 17.

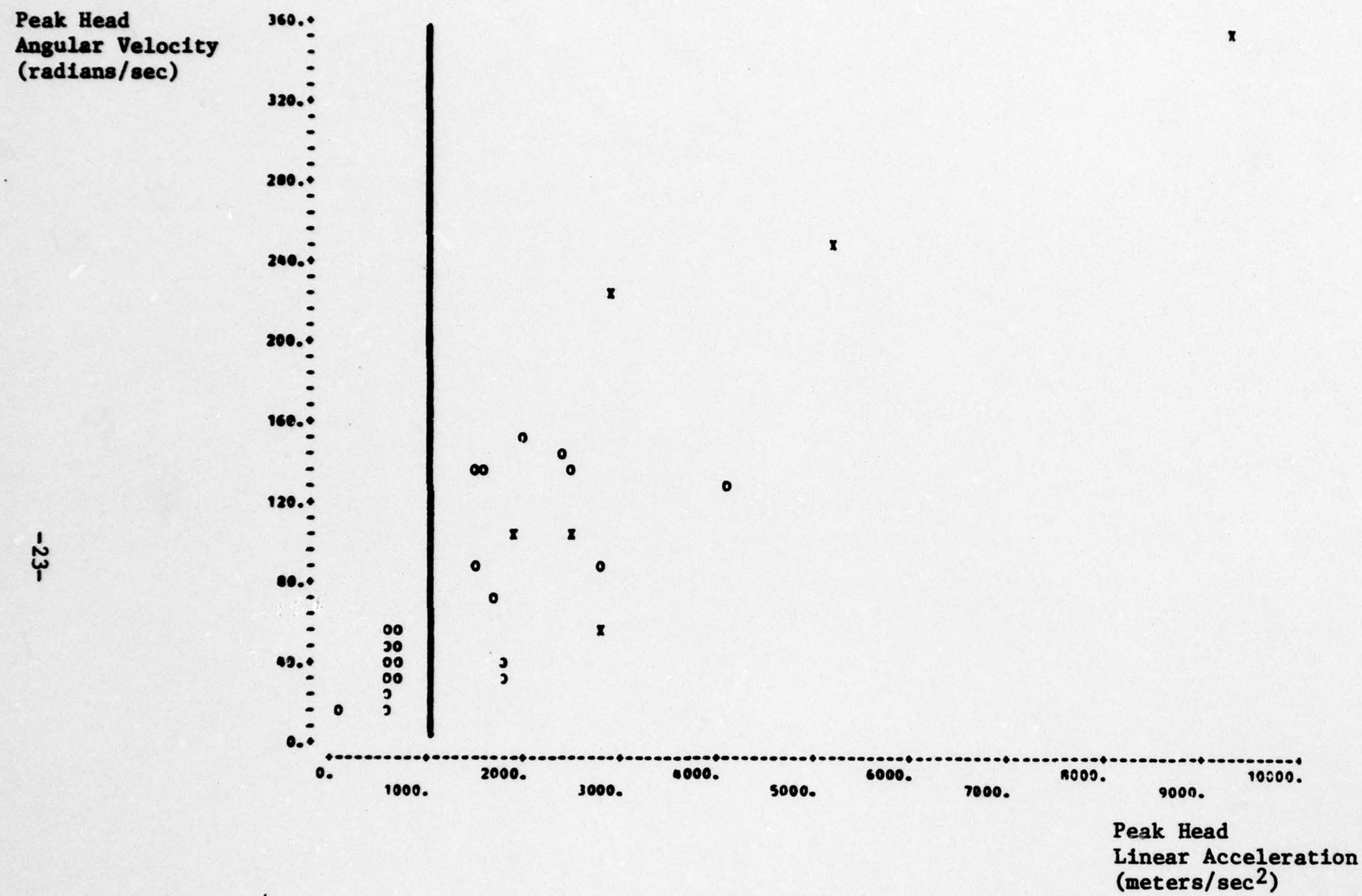

Figure 13: Boundary for Predicted Fatality Probability of 5%
(x Denotes Fatality, 0 Denotes Nonfatality)

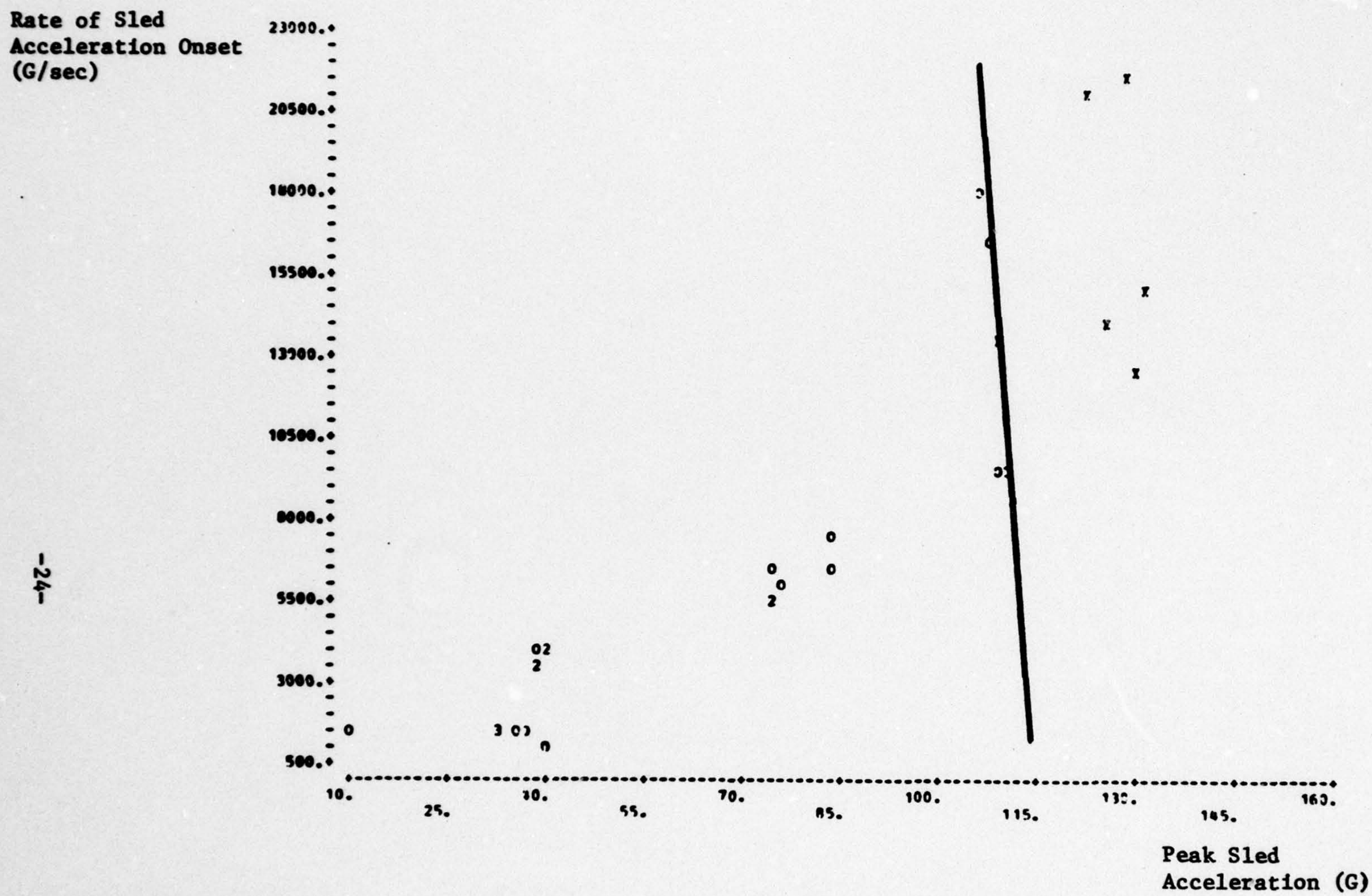

Figure 14: Boundary for Predicted Fatality Probability of 5%
(x Denotes Fatality, 0 Denotes Nonfatality)

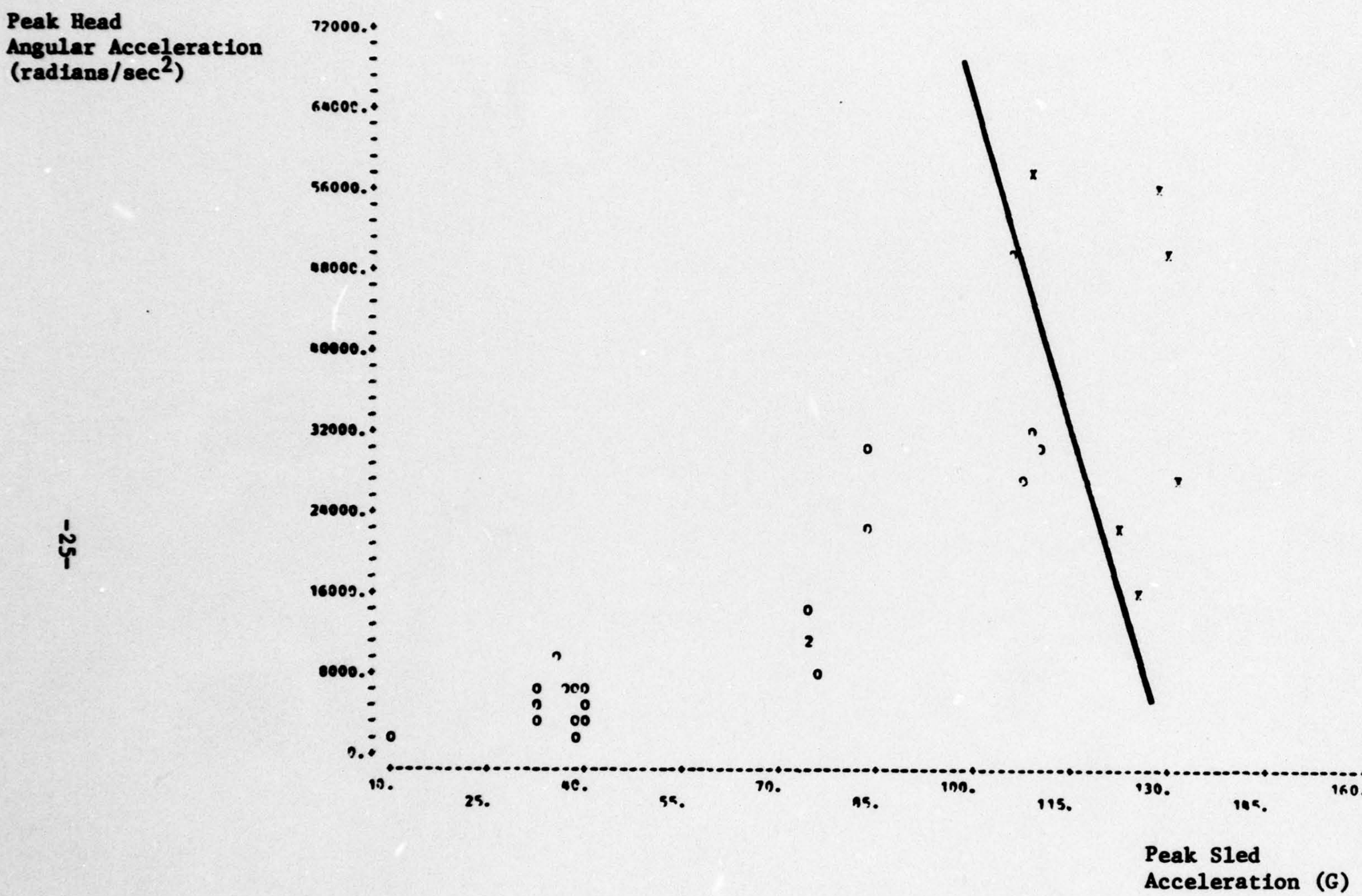

Figure 15: Boundary for Predicted Fatality Probability of 5%
(x Denotes Fatality, 0 Denotes Nonfatality)

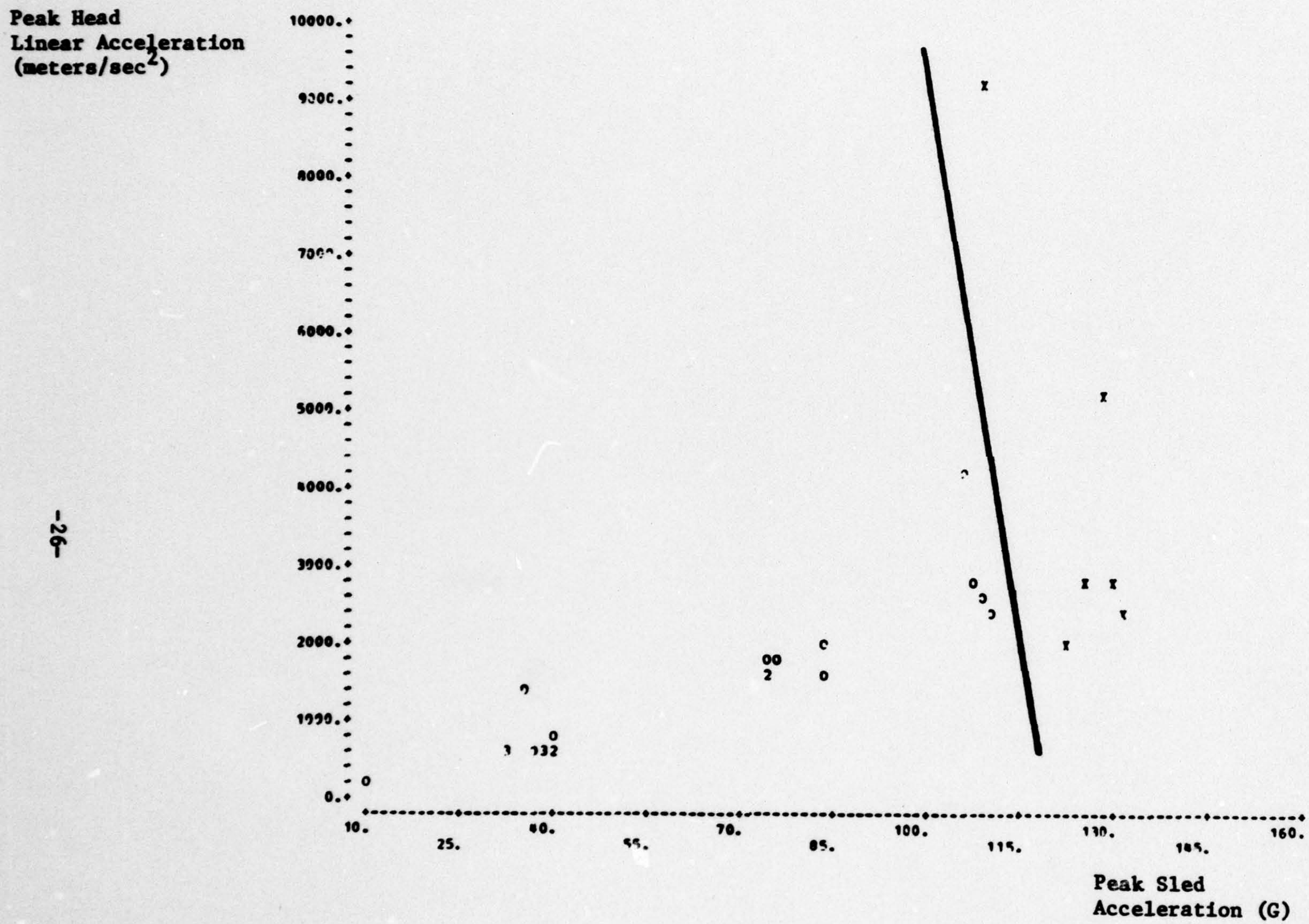

Figure 16: Boundary for Predicted Fatality Probability of 5%
(x Denotes Fatality, 0 Denotes Nonfatality)

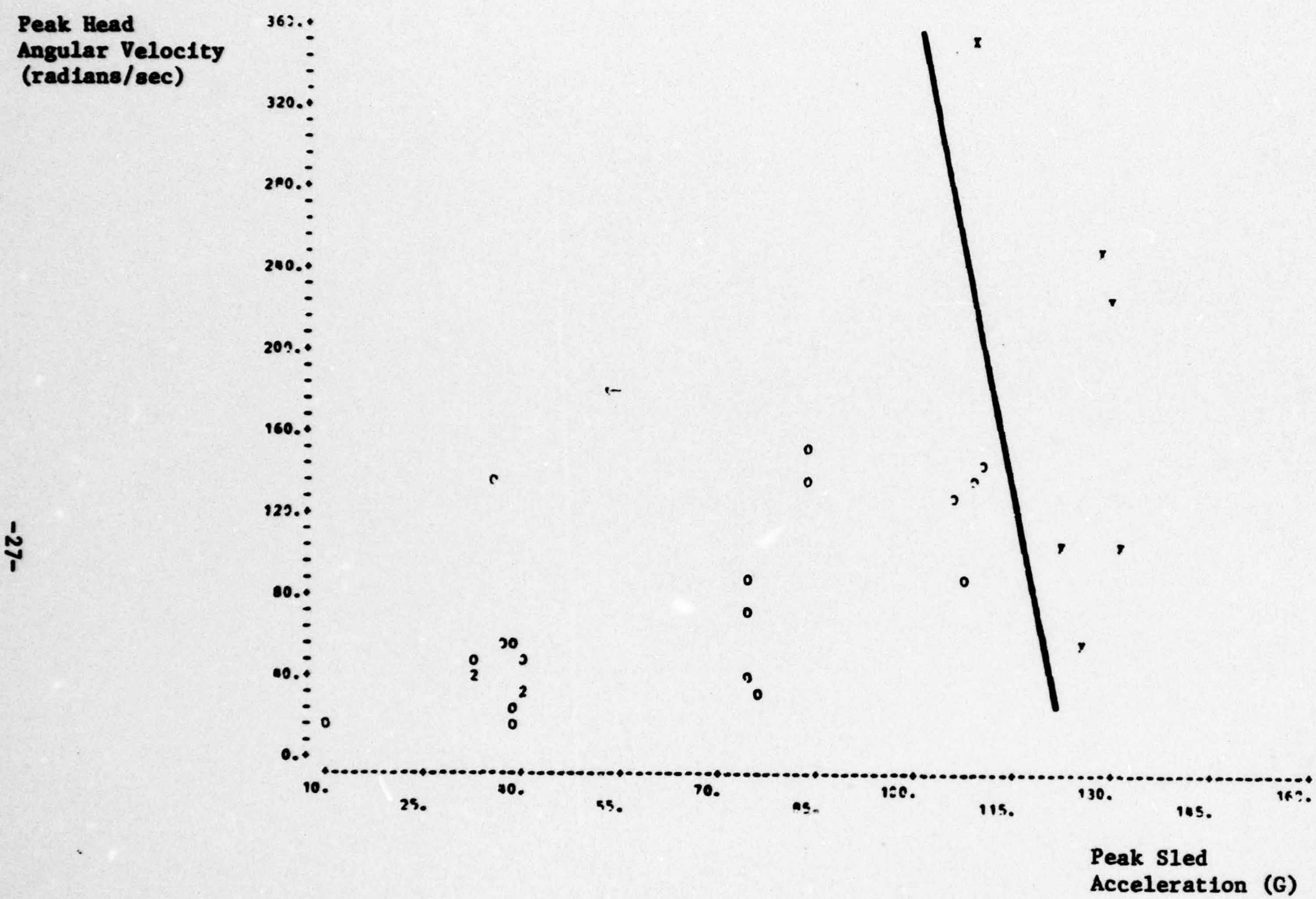

Figure 17: Boundary for Predicted Fatality Probability of 5%
(x Denotes Fatality, 0 Denotes Nonfatality)

III. SUMMARY AND DISCUSSION

Because of differing initial head position of the experimental subjects, it was postulated a priori that the sled acceleration profile would yield less sensitive independent variables than head dynamic response would. Using a common data base, two different models were constructed, one based on sled profile variables and the other based on head dynamic response variables. Although the latter model provided a reasonable fit given the small size of the data set, the other model (based on sled profile variables) resulted in a much better fit. This can be seen by comparing Figures 4 and 8.

Since it is intuitive that a model based on head dynamic response should provide predictions which are as good as or better than those from a model based on sled profile, some explanation is required. There are a few possible reasons for this anomalous result. It may be that the wrong variables were extracted from the head dynamic response time traces, and other variables would have more correctly conveyed the information within these time traces. On the other hand, the correct variables may have been selected but errors may have been present in their measurement. In addition, it is possible that the small sample size resulted in a spurious result.

It must be realized, however, that consideration of any of the three head dynamic response variables in conjunction with peak sled acceleration provides a perfectly fitting model. Thus, there is evidence that head dynamic response variables and sled profile variables may be used together to provide good results. Nonetheless, it is still an open question of why head dynamic response variables alone did not provide a model which performed as well as the one based on sled profile variables alone.

In any event, additional accelerator runs are warranted, particularly in the region defined by

$$100 < z_1 < 125$$
$$10{,}000 < z_2 < 20{,}000$$

where, as previously defined,

z_1 is peak sled acceleration measured in G's

and z_2 is rate of sled acceleration onset measured in G/sec .

This should result in valuable information around the apparent boundary between fatality and nonfatality.

IV. REFERENCES

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This report considers the application of an impact acceleration injury prediction model to observed data from a set of twenty-eight $-G_x$ accelerator runs involving subhuman primates (Rhesus monkeys) with securely restrained torso and unrestrained head. The data was collected by the Naval Aerospace Medical Research Laboratory (NAMRL) Detachment as part of its research effort on acceleration impact injury prevention.

Using a common data base, two different models were constructed, one

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based on sled profile variables and the other based on head dynamic response variables. Although the latter model provided a reasonable fit given the small size of the data set, the other model (based on sled profile variables) resulted in a much better fit. Possible explanations for this seemingly anomalous result are listed and additional accelerator runs are suggested.